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FATIGUE OF ENGINEERING MATERIALS AND STRUCTURES

The International Journal

Editor: K.J. MILLER University of Sheffield

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The International Journal

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FATIGUE OF ENGINEERING MATERIALS AND STRUCTURES

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AIMS AND SCOPE

The aim of the journal is to draw together all the scientific and technological details of current fatigue knowledge in order to assist the design engineer in overcoming his problems, the research engineer to appreciate all scientific aspects of his work, and the scientist to become more aware of the engineering problem areas.

The scope of the journal is therefore interdisciplinary and papers will be welcomed from engineers, metallurgists, materials scientists, computer scientists, physicists, chemists and mathematicians. All materials will be considered.

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INFLUENCE OF VARIOUS PARAMETERS ON THE DETERMINATION OF THE FATIGUE CRACK ARREST THRESHOLD

Members of the Fatigue Commission of the French Metallurgical Society*

(*Received in final form* 2 *February* 1981)

Abstract—This report presents the results of a round robin study on the fatigue crack arrest threshold (ΔK_{th}) of 2618 aluminium alloy and AISI 316 steel.

The main purpose of this work was to develop a method for the determination of ΔK_{th}, and to examine the influence of various test parameters on this threshold.

Among the parameters considered, only the load ratio (R) and the environment (vacuum) appear to have a significant influence on very slow fatigue crack growth rates (FCGR). Moreover, while the results obtained with the 316 steel show great scatter, the importance of the adopted procedure is pointed out.

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INTRODUCTION

THE DETERMINATION of the resistance of a material to fatigue crack propagation and the calculations of defect tolerance relies on the relationship between crack growth rate per cycle (da/dN) and the amplitude of the stress intensity factor ΔK.

In a range of rates between 10^{-3} and 10^{-5} mm/cycle, the propagation law for many materials has the following form:

$$da/dN = C \cdot \Delta K^m$$

C and m being constants depending on the material.

At lower values of the crack growth rate, it is generally found that there is a characteristic value of ΔK, called the threshold ΔK_{th}, for which the rates rapidly become very small [1–15]. This threshold ΔK_{th} constitutes a feature of the gap between crack initiation and crack growth. It has often been thought that, like the endurance limit, it could be an intrinsic property of the material.

For a given material several factors may have an influence on ΔK_{th}. Among them, the R ratio ($R = K_{min}/K_{max}$) and the environment are known to be the most important. Other factors such as the frequency may also affect the threshold behaviour. In order to offer a firmly established experimental basis for the influence of various parameters on crack growth rate at low ΔK an extensive program has been undertaken by the French Metallurgical Society. Ten laboratories were involved in this study. The main objective of this program was to determine low fatigue crack growth rates (FCGR) using a series of systematic tests in which the most significant parameters were studied.

PRESENTATION OF THE STUDY

Materials

The study was conducted on a 316 stainless steel (water-quenched from 1100°C) used in the nuclear power industry and on a 2618 (T651) aluminium alloy used in the aircraft industry for supersonic applications.

* See Appendix.

The chemical composition and the mechanical properties of the alloys are listed in Table 1.

Parameters

The various parameters investigated were the specimen type, the specimen thickness B, the crack length a, the test frequency, the waveform and the environment (air or vacuum). Tests under vacuum were carried out in a hermetically sealed chamber, at 10^{-5} torr [16]. These parameters are detailed in Table 2, with their range of variation.

General features of the procedures

The reference specimen was a compact-tension one, with a thickness $B = 20$ mm and a width $W = 2B$. Low FCGR values were obtained by using a *load shedding technique*. The standard procedures supplied to all participants were the following:

Table 1. Chemical composition and mechanical properties of the materials

2618 T 651 Aluminium alloy	Chemical composition								
	Fe	Si	Cu	Ni	Mg	Ti	Mn	Cr	Zn
	1·15	0·20	2·55	1·13	1·64	0·15	0·065	0·01	0·1
	Mechanical properties								
	$\sigma_y = 402$ MPa $\sigma_u = 447$ MPa $\varepsilon_f = 7\%$								
	$K_{Ic} = 20\ \mathrm{MPa}\sqrt{\mathrm{m}}$								
AISI 316	Chemical composition								
	C	Mn	Si	S	P	Ni	Cr	Mo	Co
	0·055	1·85	0·52	0·03	0·03	10·7	16·8	2·1	0·17
	Mechanical properties								
	$\sigma_y = 220$ MPa $\sigma_u = 580$ MPa								

Table 2. Parameters investigated

	Material	
	2618 Al	AISI 316
Specimen type	Compact tension $W = 2B$	
	CCT with $B = 20$, $W = 120$ *mm*	CCT with $B = 20$, $W = 90$ mm
Specimen thickness, B	5–40 mm	5–25 mm
Crack length	$0{\cdot}4 < \frac{a}{W} < 0{\cdot}6$	$0{\cdot}5 < \frac{a}{W} < 0{\cdot}6$ (CT) $0{\cdot}2 < \frac{2a}{W} < 0{\cdot}6$ (CCT)
Frequency	0·5–130 Hz	
Waveform	Sine, square and triangle	
Environment	Air Argon Vacuum 10^{-5} torr	Air Vacuum 10^{-5} torr
Temperature	25°C	25°C

2618 *A alloy*. Initial $\Delta K \sim 11\ \mathrm{MPa}\sqrt{\mathrm{m}}$ ($\sim K_{Ic}/2$)

$$R = \frac{P_{\min}}{P_{\max}} = 0.1$$

10% load steps when $\mathrm{d}a/\mathrm{d}N < 2\ 10^{-5}$ mm/cycle, 20% *when*

$$\frac{\mathrm{d}a}{\mathrm{d}N} > 10^{-5}\ \mathrm{mm/c}$$

crack increments between successive load sheds

$$\Delta a \geqslant \frac{1}{2\pi}\left(\frac{K_{\max}}{\sigma_y}\right)^2$$

end of test when:

$$10^{-7} < \frac{\mathrm{d}a}{\mathrm{d}N} < 10^{-6}\ \mathrm{mm/cycle}$$

and

$$0.45 < \frac{a}{W} < 0.55$$

AISI 316. Initial $\Delta K \sim 16\ \mathrm{MPa}\sqrt{\mathrm{m}}$

$$R = \frac{P_{\min}}{P_{\max}} = 0.15$$

10% load steps
crack increments ~ 0.3 mm
end of test when:

$$\frac{\mathrm{d}a}{\mathrm{d}N} \sim 10^{-7}\ \mathrm{mm/cycle}$$

and

$$\frac{a}{W} \geqslant 0.5.$$

These procedures give a decrease in ΔK with crack length of about $-0{\cdot}7$ and $-2{\cdot}2\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{mm}$ for the aluminium alloy and stainless steel respectively. These values may vary when parameters such as W, R *and* a/W were changed in order to study their influence on low FCGR.

During all the experiments, the crack was monitored on the faces of the specimen with a travelling microscope (magnification of 20 to 40).

The a versus N data were reduced by the secant method according to the ASTM procedures. At each step of the test, the value of ΔK was calculated at the middle of the crack length increment and the value of $\mathrm{d}a/\mathrm{d}N$ was taken as the average one over the crack increment.

The tests were conducted until no detectable crack propagation occurred within 10^6 cycles. The threshold value was then calculated with the load and crack length

corresponding to the previous step. In these conditions, the lowest crack growth rates obtained were close to 10^{-7} mm/c. A limited number of experiments were carried out below 10^{-7} mm/c.

RESULTS

2618 *aluminium alloy*

This alloy exhibits a typical threshold effect (Fig. 1) in the range of the crack growth rates studied, i.e. below approximately $da/dN = 10^{-6}$ mm/cycle, the slope of the da/dN versus ΔK curve is almost vertical.

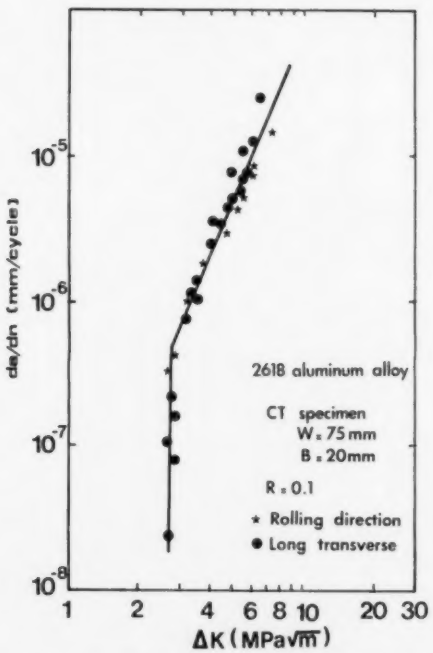

Fig. 1. Typical crack growth rate behaviour of the 2618 aluminium alloy below 10^{-5} mm/cycle observed by using the load shedding procedure.

The threshold value was determined for a rate da/dN of 10^{-7} mm/cycle. Using a standard testing procedure (i.e., a sine wave form, a frequency of 30–50 Hz, a load ratio $R = 0{\cdot}1$, CT specimen), the crack arrest threshold is 3 MPa$\sqrt{\text{m}}$ ($\pm 0{\cdot}5$ MPa$\sqrt{\text{m}}$).

The values of ΔK as a function of the various parameters studied are listed in Table 3. These values are average results for at least 3 tests.

Parameters which have little effect on the crack arrest threshold. The 2618 Aluminium alloy results of Table 3 show that the threshold is independent of the wave form and the specimen crack length over the range of $a/W = 0{\cdot}4$–$0{\cdot}6$. Figure 1 shows that it is also independent of the specimen orientation with respect to the rolling direction.

For specimen thicknesses ranging from 5 to 50 mm, the ΔK value corresponding to the rate 4×10^{-6} mm/cycle varies non systematically from 3·6 to 4·5 MPa$\sqrt{\text{m}}$. Since these

Table 3. Effect of various parameters on low FCGR of 2618 Al alloy

Parameter studied	Variation of the parameter studied	Crack growth rate (mm/cycle)	Corresponding values of ΔK ($MPa\sqrt{m}$)
Specimen thickness, B mm	5	4×10^{-6}	4·5
	10		3·8
	20		3·9
	30		4·2
	40		3·6
Specimen type	CCT	10^{-6}	3·7
	CT		3·2
Load ratio, R	0·1	10^{-7}	2·9
	0·3		2·3
	0·5		1·8
	0·7		1·2
Crack length $\frac{a}{W}$	0·4	10^{-7}	3·0
	0·5	2×10^{-7}	3·2
	0·6	10^{-6}	3·1
Frequency, Hz	0·5	10^{-6}	3·0
	40		3·2
	130		3·8
Waveform	Sine	10^{-6}	3·5
	Square		3·2
	Triangle		3·6
Environment ($R = 0·1$)	Vacuum 10^{-5} torr	10^{-7}	3·9
	Argon		3·2
	Air		2·9

differences cannot be separated from the data scatter, we must conclude that there is no effect of the thickness on the value of the threshold.

Between 0·5 and 130 Hz, frequency had very little effect on the results. Note that the threshold corresponding to 0·5 Hz was obtained by frequency reduction after the rate decreased below 10^{-6} mm/cycle (Table 3).

Specimen configuration also showed little effect on the crack arrest threshold. The results obtained for center notched and compact specimens are very similar.

Parameters which strongly affect the crack arrest threshold. The stress ratio, $R = \sigma_{min}/\sigma_{max}$, has a strong influence on the low crack growth rates of this alloy. The transition between stage I and stage II of FCGR tends to appear at lower rates when the R ratio is larger. Also, the crack arrest threshold decreases when the R ratio increases (Fig. 2). The results indicates that ΔK_{th} depends on R according to the following relationship:

$$\Delta K_{th} = 3\,(1-R)^{0·61} \text{ at } 10^{-7} \text{ mm/cycle.}$$

A similar relation was found by Klesnil and Lukas [3]:

$$\Delta K_{th} = \Delta K_{th_o}\,(1-R)^{\gamma}.$$

The environment appears to have an influence on the threshold, but less than in the region where $da/dN > 10^{-5}$ mm/cycle.

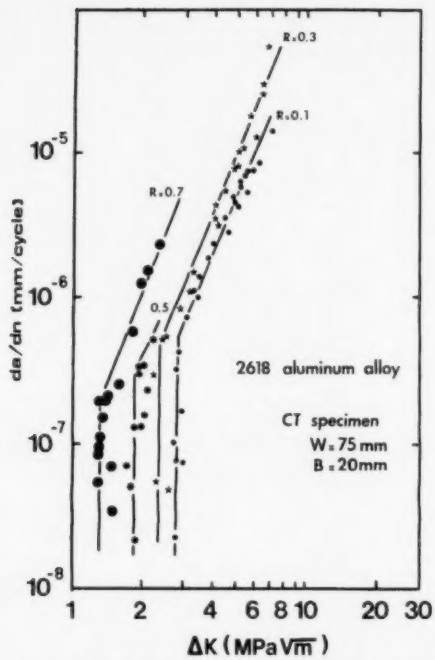

Fig. 2. Effect of the R ratio on the low FCGR of the 2618 aluminium alloy. (Two tests per value of R).

For a given value of R, the crack arrest threshold is slightly larger in dry argon than in air. In argon, for $R = 0{\cdot}1$, ΔK_{th} is equal to 3·25 MPa$\sqrt{\text{m}}$ and for $R = 0{\cdot}5$ it reaches a value of 2·15 MPa$\sqrt{\text{m}}$.

In vacuum, the difference becomes larger. Figure 3 shows that the FCGR curve obtained in vacuum does not show a well defined knee. When the stress intensity factor decreases, the crack growth rate decreases uniformly and, because of this a threshold is not as well defined as in air.

316 *stainless steel*

This stainless steel exhibits a different behaviour from that found in the aluminium alloy. The da/dN vs ΔK curve does not present a well defined knee down to 10^{-7} mm/cycle; the curve exhibits a continuous slope for crack growth rates between 10^{-7} mm/cycle and 10^{-3} mm/cycle (Fig. 4).

Some experiments carried out below 10^{-7} mm/cycle have shown the existence of a knee, in the da/dN vs ΔK curve, around 10^{-7} mm/cycle.

The results are presented in Table 4. These data cannot be considered as threshold values, but only as values of ΔK corresponding to a given crack growth rate.

The results obtained exhibited large scatter of the data. For example, Fig. 5 presents results which were obtained under the same experimental conditions, namely $R = 0{\cdot}15$ and specimens with $B = 20$ mm and $W = 2B$. For a given value of ΔK in the range $5 < \Delta K < 10$ MPa$\sqrt{\text{m}}$, the crack growth rate scatter is 1 to 4 within a given laboratory and 1 to 6 for all laboratories.

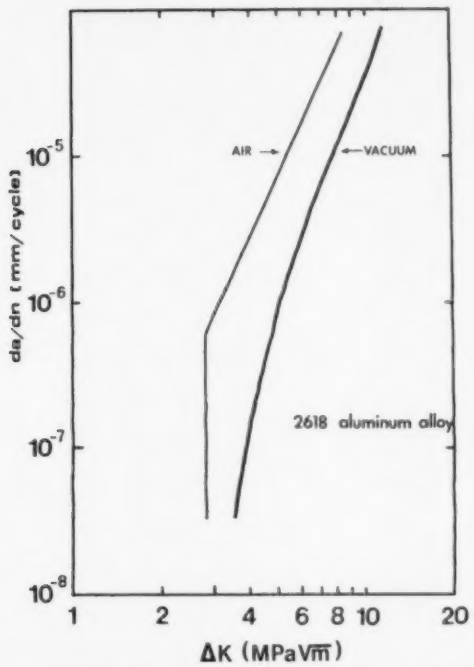

Fig. 3. Effect of the environment on the low FCGR of the 2618 aluminium alloy.

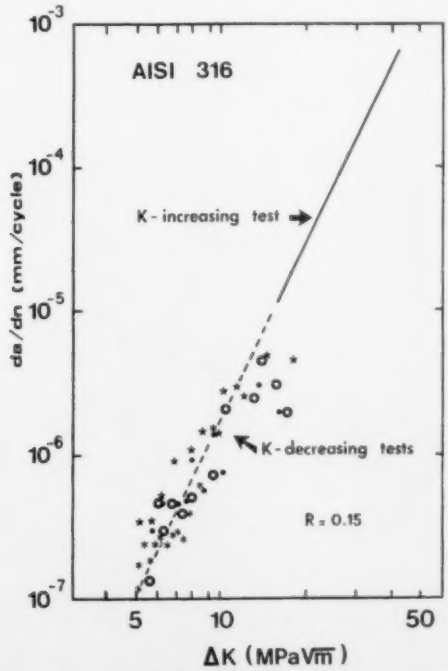

Fig. 4. Typical behaviour of the AISI 316 steel in the low FCGR range.

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Table 4. Effect of various parameters on low FCGR of 316 Steel

Parameter studied	Variation of the parameter studied	Crack growth rate (mm/cycle)	Corresponding values of ΔK (MPa$\sqrt{m}$)
Specimen thickness B (mm)	5	3×10^{-6}	8·0
	10		7·0
	20		6·5
	25		7·0
Specimen type	CCT	10^{-6}	7·2
	CT		9·0
Load ratio, R	0·1	10^{-7}	5·8
	0·6		4·2
	0·8		
Crack length $\frac{a}{W}$	0·4	10^{-7}	6·6
	0·5		5·9
	0·6		5·7
Waveform	Triangle	10^{-6}	8·5
	Square		9·6
Environment	Air	10^{-6}	9·0
	Vacuum 10^{-5} torr		8·6

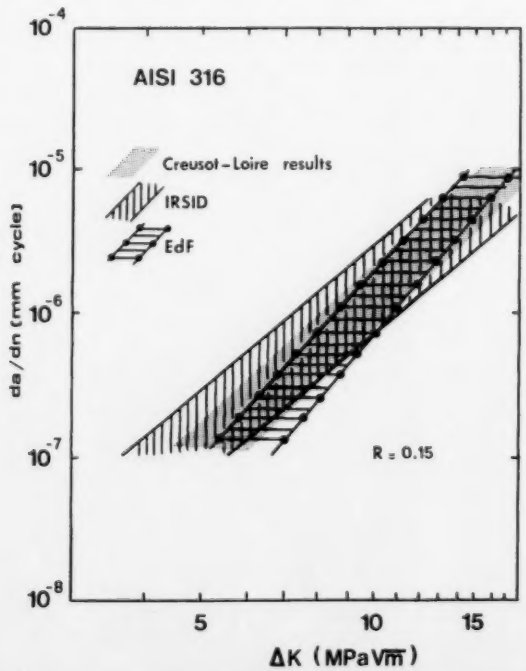

Fig. 5. Scatterbands of the low FCGR results obtained in three different laboratories.

The test parameters such as specimen type, thickness, crack length and wave form have no influence on the low FCGR region (Table 4).

The effect of the environment (air or vacuum) was found to be negligible in this material.

Only the R ratio affect the low FCGR of the 316 steel (Table 4). In this domain the value of ΔK at a given rate decreases as R increases.

DISCUSSION

2618 *Aluminium results*

The establishment of the crack arrest threshold of the 2618 aluminium alloy does not present any difficulty, and the scatter of the data among the laboratories is only $\pm 10\%$ on ΔK, which is acceptable. The difficulties which were experienced for the second alloy studied are not evident here, probably because the crack front remains almost straight in every case. Therefore, the proposed method is convenient.

The fact that the specimen geometry does not affect the results is significant, because, if the threshold criterion is to be used in design, one must ascertain that this parameter does not change with geometry.

No effect of the sampling direction was observed. This observation confirms that some metallurgical parameters (rolling direction and grain size) which are known to affect the endurance limit of 2618 alloy do not play the same role for the threshold.

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AISI 316 *results*

Scatter of the results. It was noticed previously that the FCGR variability in the investigation range could be 1 to 6 for a given value of ΔK. This is much more than the 1 to 2 variability in FCGR within the range $10^{-5} < da/dN < 10^{-3}$ mm/cycle [17]. In our opinion, there are several reasons for this.

A. The difficulty in following the fixed procedure when load shedding is manually applied to the specimen. As several days are needed to finish this type of test, it is often necessary to reduce frequency during nights in order to allow the operator to monitor crack growth. Doing so, transient phenomena may occur during the cracking process, which may influence the final result. The effect of such troubles are unpredictable and not reproducible. An optimum approach would be to carry out the load shedding with an automatically controlled testing machine.

B. The small crack increment used at each load step was not sufficient to minimize the delay observed after each load shed. The increment was chosen to be 0·3 mm because of the small value of the specimen width W.

C. The crack tunnelling effect. Figures 4 and 5 refer to surface crack length measurements: however, an examination of the fracture surfaces of cracked specimens made from 316 steel shows that the crack front curvature varies enormously from one specimen to another. In particular, it is much more accentuated in the case of tests carried out with large values of dK/da.

Moreover, for a given specimen, crack front curvature varies from one step to another one becoming accentuated as ΔK decreases (Fig. 6). We have thus calculated that the correction factor γ defined by:

$$\gamma = (\Delta K_{\text{mid-thickness}} - \Delta K_{\text{surface}})/\Delta K_{\text{surface}}$$

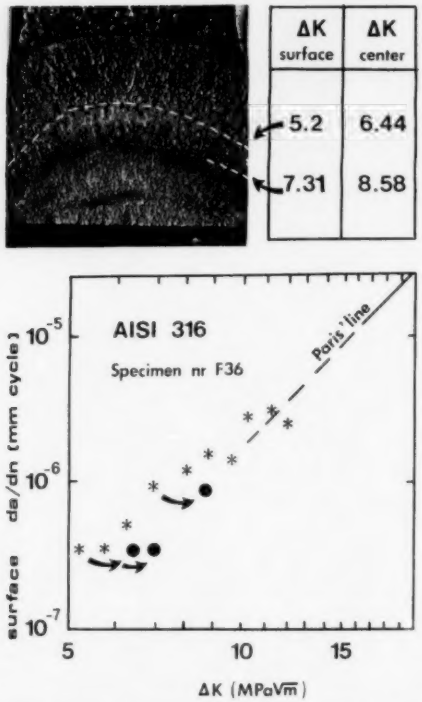

Fig. 6. Influence of crack tunnelling on the ΔK values at the centre and at the surface of the specimen.

was of the order of 22% for $\Delta K_{surface} \simeq 5\ MPa\sqrt{m}$ and 15% for $\Delta K_{surface} \simeq 10\ MPa\sqrt{m}$. As all the steps are not always well marked on the fracture surface it seems difficult to apply a precise correction.

If the crack front takes on a new curvature whenever the load amplitude varies, the mid-thickness crack growth rate of the specimen is not equal to that measured on the surface. Logically, to the ΔK correction which displaces the test points along a horizontal line must be added a (da/dN) correction which displaces these same points along a vertical line. This remark regarding the crack front curvature greatly penalizes the results of these fatigue tests at low propagation rates. They are not all representative of the real values of the threshold ΔK_{th} and of the low growth rates.

As a consequence, it seems necessary to get data about the susceptibility of a given material to crack tunnelling prior to any threshold test. In this condition, it is possible to choose the correct specimen size which minimizes the effect of crack tunnelling on ΔK values. In particular, the choice of greater values of the ratio W/B is a good way to achieve this point.

Decreasing ΔK *rate*

Generally, the load shedding rate applied to the great majority of the specimens tested in this work violated the ASTM recommendations when expressed in terms of dK/da [18]. Most of the tests were carried out under the conditions described in Table 5.

Table 5. Decreasing ΔK rates observed for various test conditions

Material	Test condition	dK/da	$\frac{1}{K}\frac{dK}{da}$
2618 Al	Standard	−0·7	−0·17 mm^{-1}
AISI 316	Standard	−2·20	−0·33 mm^{-1}
	CCT $\frac{2a}{W}$ = 0·23	−1·38	
	0·42	−1·29	
	0·62	−0·67	
	ASTM (March, 1977)	−0·3	

From Fig. 7 where CCT and CT results are compared, different FCGR curves can be drawn. It happens that the tests carried out with the lower decreasing ΔK rates give results at the upper bound of the scatterband. So, for a given value of ΔK, measured FCGR are decreasing with respect to the procedure used, according to the following order:

$$\text{CT with } \frac{2a}{W} = 0{\cdot}62$$

$$\text{CCT with } \frac{2a}{W} = 0{\cdot}42 \text{ and } 0{\cdot}23$$

finally, the standard procedure with CT (20) specimens

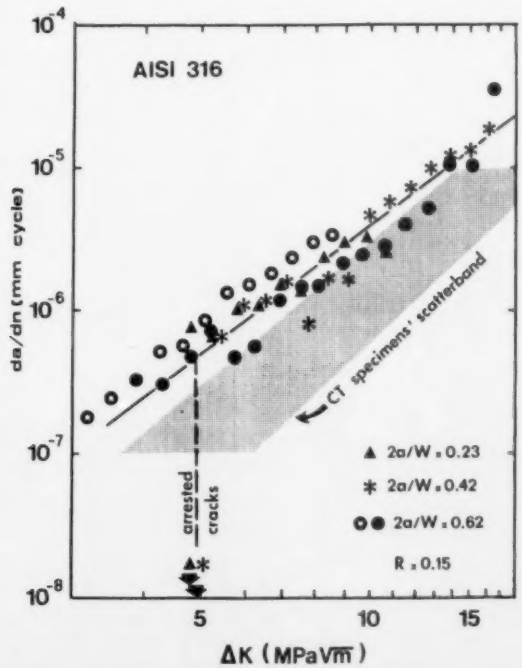

Fig. 7. Comparison between the results obtained with CT (20) specimens and CCT specimens.

The main conclusion that can be drawn from these results is that the rate of decreasing K is a parameter which has an influence on low FCGR. No effect on low FCGR can be attributed to specimen type as it is possible to observe comparative behaviour with large CT or CCT specimens.

CONCLUSIONS

This investigation has shown that different materials may exhibit different behaviours in the low FCGR range:

(1) In the case of the 2618 aluminium alloys, the existence of a crack arrest threshold has been demonstrated with no ambiguity because of the presence of a knee in the curve representing the low FCGR.

(2) In the case of the AISI 316 steel, it has not been possible to establish a vertical asymptote to the ΔK line and it appeared useful to define the value of a threshold ΔK_{th} at a prescribed low crack growth rate.

(3) The data scatter obtained at low crack growth rate ($<10^{-5}$ mm/cycle) is small for the 2618 aluminium alloy, but it is wider for the 316 steel because of the standard specimen geometry employed which causes crack tunnelling and allows only small crack increments at each load step.

(4) With the load shedding procedure used in this work, the test parameters such as the specimen geometry, thickness, crack length, test frequency and wave form, do not have any effect on the low FCGR.

(5) When the R ratio increases, the threshold ΔK_{th} decreases. Among all the parameters studied, the R ratio has a significant influence on ΔK_{th}.

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Appendix—FATIGUE COMMISSION MEMBERSHIP

The work described in this paper is part of the activities of the Fatigue Commission of The French Metallurgical Society whose president is M. G. Pomey, head of the Centre des Matériaux, Corbeil.

This program has been initiated and coordinated by C. Bathias, Professor at Université de Technologie de Compiègne, and consultant at Société Nationale Industrielle Aerospatiale.

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